

FINAL TECHNICAL REPORT

NASA Research Grant NAG5-6821

UV, Visible, and Gravitational Astrophysics Research and Analysis Program

Awarded under NASA Research Announcement 97-OSS-01

Period covered: January 1, 1998 – December 31, 2001

**POST-AGB STARS IN NEARBY GALAXIES
AS CALIBRATORS FOR *HST***

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Post-AGB Stars in Nearby Galaxies as Calibrators for *HST*

Final Report

This report summarizes activities carried out with support from the NASA Ultraviolet, Visible, and Gravitational Astrophysics Research and Analysis Program under Grant NAG 5-6821. The Principal Investigator is Howard E. Bond (Space Telescope Science Institute). STScI Postdoctoral Associates Laura K. Fullton (1998), David Alves (1998-2001), and Michael Siegel (2001) were partially supported by this grant.

The aim of the program is to calibrate the absolute magnitudes of post-asymptotic-giant-branch (post-AGB or PAGB) stars, which we believe will be an excellent new “standard candle” for measuring extragalactic distances. The argument is that, in old populations, the stars that are evolving through the PAGB region of the HR diagram arise from only a single main-sequence turnoff mass. In addition, theoretical PAGB evolutionary tracks show that they evolve through this region at constant luminosity; hence the PAGB stars should have an extremely narrow luminosity function. Moreover, as the PAGB stars evolve through spectral types F and A (en route from the AGB to hot stellar remnants and white dwarfs), they have the highest luminosities attained by old stars (both bolometrically and in the visual band). Finally, PAGB stars of these spectral types are very easily identified, because of their large Balmer jumps, which are due to their very low surface gravities.

Our approach is first to identify PAGB stars in Milky Way globular clusters and in other Local Group galaxies, which are at known distances, and thus to measure accurate absolute magnitudes for the PAGB stars. With this Milky Way and Local Group luminosity calibration, we will then be in a position to find PAGB stars in more distant galaxies from the ground, and ultimately from the *Hubble Space Telescope*, and thus derive distances. These PAGB stars are, as noted above, the *visually brightest members of Population II*, and hence will allow distance measurements to galaxies that do not contain Cepheids, such as elliptical galaxies, as well as distances to spirals using PAGB stars in their halos. Moreover, the method is entirely independent of Cepheids, and thus provides a direct test of the Cepheid distance scale. The program will also provide information on the evolutionary lifetimes of PAGB stars.

Our observational technique is CCD photometry. We use the standard *BVI* filters, to which we add a Gunn *u* filter that lies entirely below the Balmer discontinuity ($\lambda < 3650 \text{ \AA}$) and thus measures the size of the Balmer jump. Basically, we identify stars that are blue in $B - V$ and $V - I$ (i.e., A-F stars), but “red” in $u - B$ (i.e., having a large Balmer discontinuity).

We acquired *uBVI* CCD data in the halos of the spirals M31 and M33, and in the dwarf elliptical NGC 205 and several other galaxies in the Local Group, during observing runs at the Kitt Peak 4-m telescope with its prime-focus 2048×2048 CCD camera. More recently we also used the wide-angle Mosaic camera on the KPNO 4-m telescope to obtain frames in the Local Group galaxy IC 1613, four dwarf irregulars just outside the Local Group (Leo A, Sextans A and B, and GR 8), and in the halos of four galaxies in the M81 group: NGC 2366, NGC 2403, NGC 4236, and M81 itself.

During an even more recent run at Cerro Tololo (November 2001), Siegel used the CTIO 4-m Mosaic camera to survey the halos of several spiral galaxies in the nearby Sculptor Group, including NGC 253 and NGC 300.

With UVGA support, we also completed the observing for a program aimed at searching most of the Milky Way globular clusters for PAGB stars, with 0.9-m telescopes

at KPNO and CTIO. We predict that there will be about a dozen A-F PAGB stars in the entire Milky Way globular-cluster system, which will play a crucial role in the luminosity calibration. We have good CCD frames, generally reaching down to the horizontal branch, for some 100 Milky Way globular clusters. To date, there are 3 well-established A-F PAGB stars in Milky Way globulars: one in ω Centauri, and two in NGC 5986. Siegel is well along in analyzing these frames.

During the grant period, we completed a photometric study of NGC 5986, based on 0.9-m CCD frames obtained by Bond and analyzed by Alves and an STScI summer student worker from the University of Minnesota, Chris Onken. The color-magnitude diagram of the cluster yields a new distance determination of 10.7 kpc. These data confirm that the two PAGB stars in NGC 5986 have the same absolute magnitudes to better than 0.1 mag, thus supporting their utility as standard candles. The mean absolute magnitude, including also the PAGB star in ω Centauri, is $M_V = -3.28 \pm 0.07$. This study has been published in the *Astronomical Journal*.

As described above, for purposes of identifying PAGB stars, we are developing a new “ $uBVI$ ” photometric system, based on the u filter of the Gunn-Thuan system combined with the standard BVI filters of the Johnson-Cousins system. The advantage of Gunn u over Johnson U is that the former filter’s bandpass is entirely below the Balmer discontinuity. PAGB stars, which are low-mass stars in transitory high-luminosity evolutionary stages, will have extremely low surface gravities, and hence, as they pass through spectral types F and A, will have very large Balmer jumps. This is the distinctive feature that gives them unique $u - B$ colors, and allows PAGB stars to be detected readily throughout the Local Group. We have made extensive observations of Landolt standard stars, to which we are adding a calibration of the u filter, in order to develop a network of $uBVI$ standards around the celestial equator.

Alves (now at Columbia University) and Siegel have been working on completing the calibration of the $uBVI$ system, by combining all of our frames of the Landolt standard fields obtained throughout all of the lengthy observing. This is a major undertaking, involving analysis of a total of 12 0.9-m observing runs (46 individual nights) with extensive CCD observations of the standard fields; including the object frames as well as the standard fields, there are some 10,000 CCD frames. This standardization effort is nearly completed, and a progress report was presented at the January 2001 AAS meeting. This work, in turn, will be the basis for calibrating the PAGB absolute magnitudes in Milky Way globular clusters, the Local Group, and the Sculptor and M81 Groups.

Bond completed a theoretical $\log g$ calibration of the $uBVI$ photometry, using published model stellar atmospheres and convolving the theoretical fluxes with the filter and detector sensitivity functions. This refinement will allow us to select only stars that have the Balmer jumps of low-gravity stars, and to reject other contaminants, such as background unresolved blue galaxies and foreground horizontal-branch stars of our own galaxy’s halo.

Some astrophysical results of the above work were presented by Bond at the workshop on post-AGB stars in Torun, Poland, in August 2000. We have a preliminary result on NGC 205, a dwarf elliptical companion of M31, whose PAGB stars indicate that it is ~ 100 kpc further away than M31 itself, in spite of the usual assumption that it is at the same distance. Thus, our program is yielding surprises even within the Local Group. Counts of PAGB candidates in the halo of M31 imply that their lifetimes are $\sim 25,000$ yr, in reasonably good agreement with theoretical predictions.

We have been approved for a spectroscopic program, in which we will use the 6.5-m

MMT telescope to obtain spectra of \sim two dozen individual PAGB candidates in the M31 halo. Unfortunately, due to instrumental problems at the MMT, these observations were postponed to the fall of 2002.

In a future extension of this work, we plan to initiate studies of an entirely new class of standard candles among Population I stars: luminous A- and F-type supergiants. These objects are the visually brightest stars that exist, reaching to absolute visual magnitudes as bright as $M_V \simeq -9$. Model stellar atmospheres show that the size of their Balmer jumps is directly related to their absolute magnitudes, so that our $uBVI$ system should be capable of determining their M_V 's. In collaboration with Dr. R. M. Humphreys (University of Minnesota), we will propose to use the KPNO 4-m and Mosaic camera, with which we will survey the entire M31 and M33 galaxies in order to identify all of their luminous Pop I A-F supergiants. (Surprisingly, there has never previously been a general survey of M31 and M33 for A-F supergiants.) In addition to calibrating these stars as a new Pop I standard candle, our survey will provide useful targets for NASA's Space Interferometry Mission, which should be capable of detecting their proper motions due to the rotations of M31 and M33 once we have provided a list of M31/M33 members bright enough for SIM to observe.

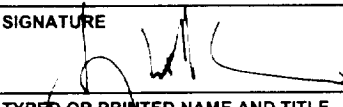
The ultimate aims of the program are (a) to determine the absolute magnitudes of PAGB stars and the metallicity dependence, if any, thus establishing a "Population II" distance scale that will be entirely independent of Cepheid variables; and (b) to attempt also to calibrate Population I A-F supergiants as even more luminous standard candles. On this basis, future *HST* observations can establish the distances to galaxies well beyond M81, including (in the case of Pop II PAGB stars) elliptical galaxies that do not contain Cepheid variables. With *HST*'s Wide Field Camera 3—which will be UV-optimized and, due partly to Bond's advocacy, will have a high-throughput filter similar to our ground-based u —we expect to be able to measure distances directly to as far out as the giant elliptical galaxy M87 in the Virgo Cluster with great efficiency and accuracy, using our post-AGB standard candles. The new Pop I A-F supergiant candles could be detected with *HST* and WFC3 as far out as the Coma Cluster.

Publications 1998–present

1. H. E. Bond and R. Ciardullo
 "Distance to the Planetary Nebula NGC 246 from the Resolved Companion of its Central Star"
Publ. Astron. Soc. Pacific, **111**, 217, 1999.
2. H. E. Bond and L. K. Fullton
 "Post-AGB Stars in the Halo of M31 and the Implied Masses of Halo White Dwarfs"
 In *Eleventh European Workshop on White Dwarfs*, ed. J.-E. Solheim and E. G. Meistas (San Francisco: Astronomical Society of the Pacific), p. 439, 1999.
3. H. E. Bond, D. R. Alves, and C. Onken
 "Two Post-AGB A-F Stars in the Globular Cluster NGC 5986"
Bull. A.A.S., **196**, 41.10, 2000.
4. E. S. Cheng and 30 coauthors (the WFC3 SOC and GSFC/STScI staff), including H.E.B.
 "Wide Field Camera 3 for the *Hubble Space Telescope*"
Proc. SPIE, **4013**, 367, 2000.

5. M. D. Albrow and 20 co-authors, including H. E. Bond
 "Detection of Rotation in a Binary Microlens: PLANET Photometry of MACHO 97-BLG-41"
Astrophys. J., **534**, 894, 2000.
6. D. R. Alves and H. E. Bond
 "Calibration of the *uBVI* Photometric System and the Surface Gravities of Post-AGB Standard Candles"
Bull. A.A.S., **197**, 104.06, 2001.
7. D. R. Alves, H. E. Bond, and C. Onken
 "CCD Photometry of the Globular Cluster NGC 5986 and Its Post-Asymptotic-Giant Branch and RR Lyrae Stars"
Astron. J., **121**, 318, 2001.
8. H. E. Bond, K. Exter, and D. L. Pollacco
 "The Eclipsing Nucleus of the Ring Planetary Nebula SuWt 2"
Bull. A.A.S., **199**, 136.07, 2001.
9. H. E. Bond and D. R. Alves
 "Post-AGB Stars in Globular Clusters and Galactic Halos"
 In *Post-AGB Objects as a Phase of Stellar Evolution*, Proceedings of the Toruń Workshop, ed. R. Szczerba and S. K. Górny, (Dordrecht: Kluwer), p. 77, 2001. (also available at astro-ph/0104096)

FEDERAL CASH TRANSACTIONS REPORT <i>(See instructions on the back. If report is for more than one grant or assistance agreement, attach completed Standard Form 272A.)</i>		OMB APPROVAL NO. 0348-0003 1. Federal sponsoring agency and organizational element to which this report is submitted NASA Goddard Space Flight Center Accounting Branch Code 151-2 Greenbelt MD 20771	
2. RECIPIENT ORGANIZATION Name: Space Telescope Science Institute Number and Street: 3700 San Martin Drive City, State and ZIP Code: Baltimore, MD 21218		4. Federal grant or other identification number NAG5-6821	5. Recipient's account number or identifying number J0133
		6. Letter of credit number 80005122	7. Last payment voucher number n/a
		Give total number for this period	
		8. Payment Vouchers credited to your account	9. Treasury checks received (whether or not deposited)
3. FEDERAL EMPLOYER IDENTIFICATION NO.		10. PERIOD COVERED BY THIS REPORT	
86-0138043		FROM (month, day, year) 1/1/98	TO (month, day, year) 12/31/01
11. STATUS OF FEDERAL CASH <i>(See specific instructions on the back)</i>	a. Cash on hand beginning of reporting period		\$
	b. Letter of credit withdrawals		158,916.00
	c. Treasury check payments		0.00
	d. Total receipts (Sum of lines b and c)		158,916.00
	e. Total cash available (Sum of lines a and d)		158,916.00
	f. Gross disbursements		158,916.00
	g. Federal share of program income		
	h. Net disbursements (Line f minus line g)		158,916.00
	i. Adjustments of prior periods		
	j. Cash on hand end of period		\$
12. THE AMOUNT SHOWN ON LINE 11j, ABOVE, REPRESENTS CASH REQUIREMENTS FOR THE ENSUING Days		13. OTHER INFORMATION	
		a. Interest income	\$
		b. Advances to subgrantees or subcontractors	\$
14. REMARKS <i>(Attach additional sheets of plain paper, if more space is required)</i> Total award amount \$159,000.00 FINAL 272 report for J0133			

15. CERTIFICATION			
I certify to the best of my knowledge and belief that this report is true in all respects and that all disbursements have been made for the purpose and conditions of the grant or agreement.	AUTHORIZED	SIGNATURE 	DATE REPORT SUBMITTED 02/10/2003
	CERTIFYING OFFICIAL	TYPED OR PRINTED NAME AND TITLE Amy Garrett Power Accountant apower@stsci.edu	TELEPHONE <i>(Area Code, Number, Extension)</i> 410-338-4801

THIS SPACE FOR AGENCY USE

Space Telescope Science Institute
Final Property/Inventory Report for Contract – Grant Number
NAG5 – 6821
STScI Project No.: J0133
As of 07/22/2002
For dollar values greater than 5,000.00 and less than 100,000,000.00

Negative report.

NASA GRANTEE NEW TECHNOLOGY SUMMARY REPORT

NASA requires each research grantee, research contractor, and research subcontractor to report new technology to the NASA Commercial Technology Office. For that purpose, the following reports and corresponding schedules are provided:

<u>Title of Report</u>	<u>Form Number</u>	<u>Timetable</u>
New Technology Disclosure	NASA Form 1679	The grantee discloses <i>each</i> discovery of new technology individually, at the time of its discovery
NASA Grantee New Technology Summary Report (checkmarked "Interim")	NASA C-3043	For multi-year grants, the grantee summarizes the previous year's disclosures on an annual basis. The first Interim New Technology Summary Report is due exactly 12 months from the effective date of the grant. Future reports are due annually, thereafter.
NASA Grantee New Technology Summary Report (checkmarked "Final")	NASA C-3043	The grantee submits a cumulative summary of all disclosed technologies. The Final New Technology Summary Report is submitted immediately following the grant's technical period of performance.

Grantee Name:	<u>Dr. Howard Bond</u>		
Grantee Address:	<u>Space Telescope Science Institute</u> <u>3700 San Martin Drive</u> <u>Baltimore, Maryland 21218</u>		
Telephone No.:	<u>410 338-4364</u>		
NASA Grant No:	<u>NAG5-6821</u>	Grant Completion Date:	<u>12/31/01</u>
NASA GM:	<u>Phillipe Crane</u>	Report Submitted by:	<u>Jeannine N. Luers</u>

New technology should be reported whether or not it is or may be patentable.

Large business contractors and subcontractors must disclose all reportable items to NASA. Reportable items as used in NASA contracts (or subcontracts) with large businesses means any invention, discovery, improvement, or innovation, whether or not patentable, conceived or first actually reduced to practice in the performance of work under a NASA contract (or subcontract). Reportable items include, but are not limited to, new processes, machines, manufactures, and compositions of matter, and improvements to, or new applications of, existing processes, machines, manufactures, and compositions of matter. Reportable items also include new computer programs, and improvements to, or new applications of, existing computer programs, whether or not copyrightable.

Small business, nonprofit organization, and college and university contractors and subcontractors must disclose all subject inventions to NASA. Subject inventions as used in NASA contracts (or subcontracts) with other than large businesses means any invention or discovery which is or may be patentable and is conceived or first actually reduced to practice in the performance of work under a NASA contract (or subcontract). Subject inventions include any new process, machine, manufacture, or composition of matter, including software, and improvements to, or new applications of, existing processes, machines, manufactures, and compositions of matter, including software.

Subject to approval by contractors (or subcontractors) who retain or obtain title to subject inventions or reportable items, all such reported items are evaluated for publication in NASA Tech Briefs. If an item is published in NASA Tech Briefs, the innovator receives a monetary award from NASA.

NASA GRANTEE NEW TECHNOLOGY SUMMARY REPORT

General Information

1. Type of Report: ☐ Interim ☒ Final Reporting Period: 01/01/98 - 12/31/01
2. Size of Business: ☐ Large ☐ Small ☐ College/ University ☒ Nonprofit Organization
3. Have any reportable items or subject inventions resulted from work performed under this contract during this reporting period? ☐ Yes ☒ No
4. Are New Technology Items being disclosed (NF 1679 or equivalent) with this Summary Report?
☐ Yes ☒ No

• New Technology Items

Please provide the title(s) of all new and previously disclosed new technology items conceived or first reduced to practice under this grant. Use a separate piece of paper if additional space is required.

<u>Title</u>	<u>Internal Docket Number</u>	<u>Patentable Item</u>	<u>Patent Appl. Filed</u>	<u>Patent Appl. Not Filed</u>
• NONE		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
• _____	_____	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
• _____	_____	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
• _____	_____	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
• _____	_____	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

• Grant Subcontractors

Please complete the following section listing all research subcontractors participating to date. Include each subcontractor's name, address, contact person, telephone number, and the subcontract award date. Use a separate piece of paper if additional space is required.

NONE

<p>_____</p> <p>_____</p> <p>_____</p> <p>_____</p> <p>Date of Award: _____</p> <p>_____</p> <p>_____</p> <p>_____</p> <p>Date of Award: _____</p>	<p>_____</p> <p>_____</p> <p>_____</p> <p>_____</p> <p>Date of Award: _____</p> <p>_____</p> <p>_____</p> <p>_____</p> <p>Date of Award: _____</p>
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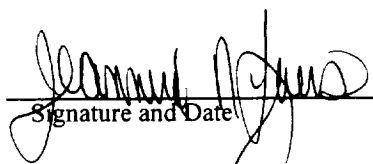
• Certification

I certify that active and effective procedures ensuring prompt identification and timely disclosures of reportable new technology items have been followed. Furthermore, I certify that all new technology items required to be disclosed and conceived during the period identified on this form have been disclosed to NASA.

Jeannine N. Luers

Sponsored Programs Administrator I

Name and Title of Authorized Official


7/23/02
 Signature and Date